
Thermal Expert System (TEXSYS) Final Report—Systems Autonomy Demonstration Project Volume 1 – Overview

B. J. Glass, Editor

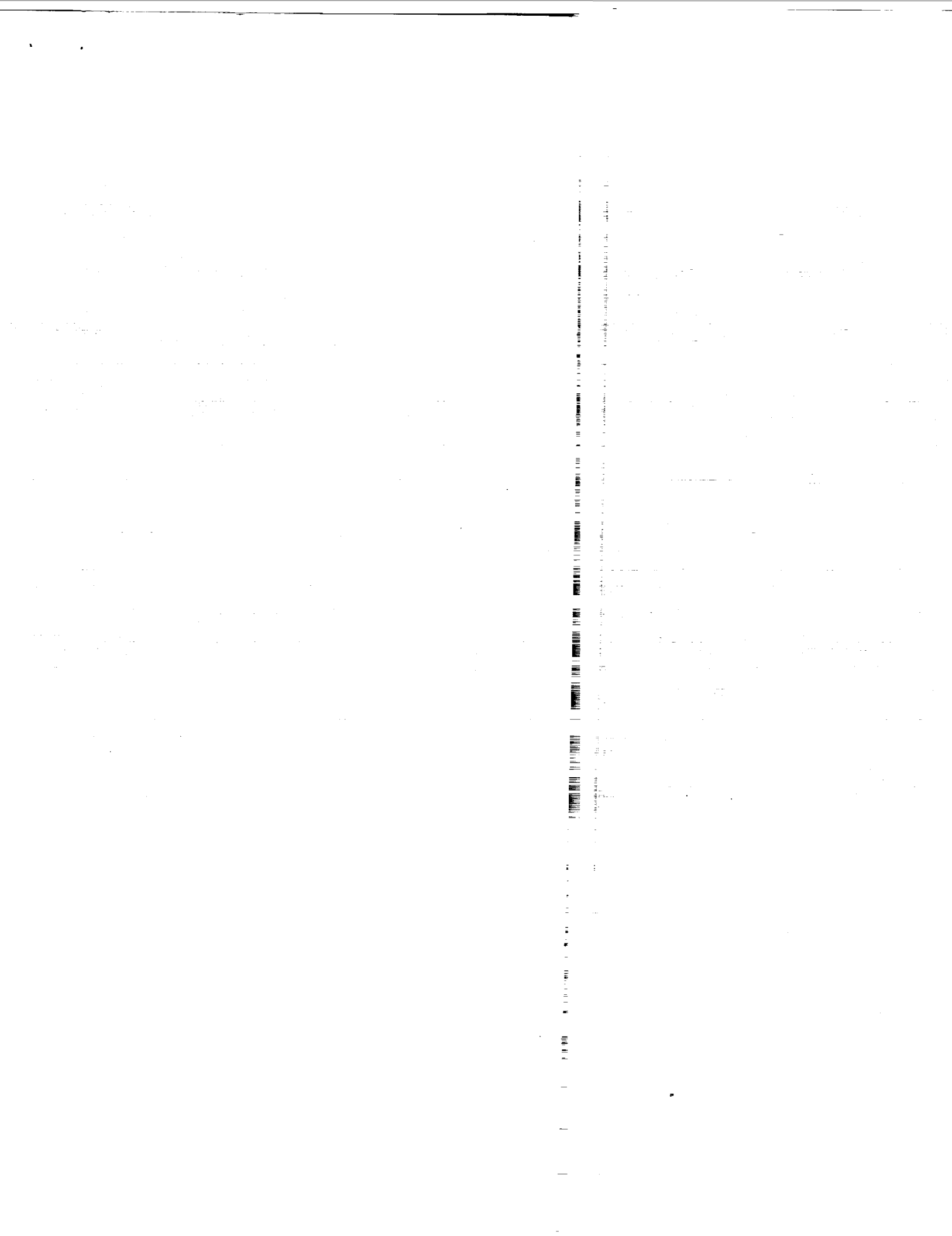
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B. J. Glass, Editor, Ames Research Center, Moffett Field, California

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National Aeronautics and
Space Administration

Ames Research Center
Moffett Field, California 94035-1000

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1. Introduction

1.1 Complex space-based systems need constant monitoring

Some complex space-based systems require constant monitoring -- parameters, configuration, and component condition changes with time. Current operational practice often requires human operators to scan telemetry, watching for deviations from expected performance. In real-time, large-scale applications this often proves expensive, since many operators are required given the data processing limitations of humans. By automating some or most of the fault detection and isolation, recovery, and control of these dynamic systems, the need for direct human intervention may be reduced.

The objective of the Systems Autonomy Demonstration Project (SADP) was to develop and validate a knowledge-based system for real-time control and fault detection, isolation and recovery (FDIR) of a complex prototype space subsystem. This two-volume report describes the technical and programmatic results of SADP, which was a joint effort between NASA's Ames Research Center (ARC) and Johnson Space Center (JSC). In addition to the significant technical challenges of SADP, cultural differences between the operationally-oriented JSC organization and the research-oriented ARC organization had to be overcome before artificial intelligence software could be integrated with a live testbed.

A prototype thermal control system, or thermal bus, for the Space Station Freedom (SSF) was selected as a representative system for a symbolic control application, the Thermal Expert System (TEXSYS). In the course of TEXSYS development, ARC created the expert system and operator interface software, while JSC was responsible for data acquisition and control software, providing thermal expertise, and testbed operations. At ARC, a thermal brassboard originally built by Sundstrand Aviation for KC-135 zero-gravity tests was employed for TEXSYS development and demonstrations. The thermal bus used for TEXSYS tests at JSC was the Boeing Aerospace Thermal Bus System (BATBS) resident at JSC. Both thermal systems followed the same Sundstrand design -- a complex, self-balancing system, described by many independent parameters. The nonlinearity of this particular thermal bus architecture has thus far made conventional dynamic numerical simulation infeasible.

1.2 Potential safety and cost improvements achieved by automating

The patient analysis required to detect very low frequency anomalies is a task that human beings dislike and perform poorly. Unlike expert systems, human operators may become inattentive, fatigued, or need to attend to bodily functions. Automated trend analysis may detect slow degradation and other incipient failures before they impact mission performance or exceed safety limits. Given continuous monitoring of manned space systems, cost savings may also be realized by automating the mundane monitoring and troubleshooting tasks -- thereby freeing crew time and reducing the level of required ground staffing.

2. Project Goals

2.1 Technical Goals: Real-time knowledge-based control

The objective of the Systems Autonomy Demonstration Project was to develop and validate a knowledge-based system for real-time control and fault detection, isolation and recovery (FDIR) of a complex space subsystem. The software thus developed was to be capable of diagnosis of all major thermal bus failure modes, and had to exhibit real-time nominal control as well as real-time correction of at least a few failures. A prototype thermal control system, or thermal bus, for Space Station Freedom was selected as a representative system and the TEXSYS (Thermal Expert System) was created.

2.2 Institutional Goals

From the initial 1986 SADP Project Plan [1]:

"The broad objectives of this demonstration project were to provide:

Technical base of in-house personnel and development tools to facilitate AI technology transfer.

Technology focus for Automation research and development in support of NASA's space programs.

Means for validation and demonstration of Automation technology prior to transfer to Agency programs.

Credibility of Automation technology within NASA.

Credibility of NASA AI expertise to the outside AI community."

A specific objective of this project was to provide:

"A technology demonstration to establish automation requirements of systems operations techniques for TCS [Thermal Control System] configuration monitoring, systems status, fault identification/ isolation/ diagnosis, and reconfiguration."

3. SADP Organization: geographically diffuse

The project was a joint effort of four divisions at two NASA centers. Project management, the expert system development, and initial TEXSYS testing with the Sundstrand thermal brassboard were all conducted by the Information Sciences Division at ARC. The Aerospace Human Factors Division at Ames designed the Human Interface to TEXSYS (HITEX). Domain expertise, the thermal bus and control systems were provided by the Crew and Thermal Systems Division at JSC. The Systems Development and Simulation Division at JSC built the TEXSYS Data Acquisition System (TDAS) and managed the systems integration and testing effort at JSC. Funding was provided through FY88 for early work on a combined Power-Thermal demonstration scheduled to follow the standalone TEXSYS demonstration. Towards this end, the Automation Power Expert (APEX) system at NASA-Lewis Research Center was begun under the auspices of the SADP, but was later separated into an independent effort.

4. Technical Approach

4.1 Hardware: two-phase thermal bus

The Boeing Aerospace Thermal Bus System (BATBS), targeted in the final TEXSYS demonstration at JSC, is the baseline thermal architecture for the SSF external thermal bus. This thermal bus consists of 5 major component types - evaporators, which collect heat by evaporation of ammonia; condensers, which reject heat to the radiators by ammonia condensation; a Rotary Fluid Management Device (RFMD), which acts as a zero-gravity pump; a Back Pressure Regulating Valve (BPRV), which controls the temperature of the bus; and an accumulator, which acts as a reservoir of vapor and fluid. The bus is instrumented with 86 temperature sensors, 9 pressure sensors, 13 delta pressure sensors, 8 flowmeters, 2 accumulator position sensors, 16 solenoid valves, a RFMD power sensor, a RFMD speed sensor, and a position indicator for the BPRV. Also provided are 30 calculated parameters such as heat load applied to the evaporators. A commercial automated control package (FLEXCON, from GeoControl Systems, Inc.) is used in the Thermal Test Bed at JSC and is attached to the bus to provide data acquisition, limited automated control and manual controls. The Sundstrand thermal brassboard used at ARC was a smaller version of

the BATBS with fewer heat exchangers. This kind of test bed proved an excellent environment for the TEXSYS project, providing a real-time electromechanical system of tractable complexity, a variety of sensors similar to flight hardware and a controlled test environment.

4.2 Multi-processor architecture

The TEXSYS system consists of three main components: the thermal expert system (TEXSYS), a human interface to TEXSYS (HITEX) and a data acquisition system attached to the automated control package. The TEXSYS architecture is shown in Figure 1.

TEXSYS communicates with the users through HITEX, which was designed for use by thermal engineers. HITEX provides a variety of textual and graphical displays to observe the state of the thermal bus and the expert system, and is used for demonstrating possible flight system operator interface capabilities. It presents this information on two user configurable monitors, with a keyboard and mouse shared between them. A monochrome graphics monitor reports on the expert system, showing information such as the currently active tasks, faults diagnosed, instructions to the user and explanations. This monitor is also the place where user input to the expert system is made via the mouse or keyboard. A color graphics monitor is used to display the state of the thermal bus in several different ways. Each monitor screen is divisible into multiple tiled windows and includes a fixed menu of icons used to initiate actions. Configuration of the screens is made from a series of pop-up menus and type-in windows triggered by mouse clicks on menu icons.

As was shown in Figure 1, the TEXSYS and HITEX systems are linked to the control system of the bus by the TEXSYS Data Acquisition System (TDAS) [2]. The prototype TDAS was created in 1986-87 by Lawrence Livermore National Laboratory (LDAS), and was used at ARC with the Sundstrand brassboard. The current TDAS was written by the Systems Development and Simulation Division at JSC.

TEXSYS supplies TDAS with lists of sensors whose values are of current interest to TEXSYS and HITEX. To reduce the amount of data to be processed, each sensor has associated with itself a set of deadbands and significance limits on TDAS. TDAS scans the data from the FLEXCON-based Data Acquisition and Control System (DACS) database at each update, in this case every five seconds, and calculates the trend and long term trends of the analog readings. Comparing current and previous

OVERVIEW OF TEXSYS

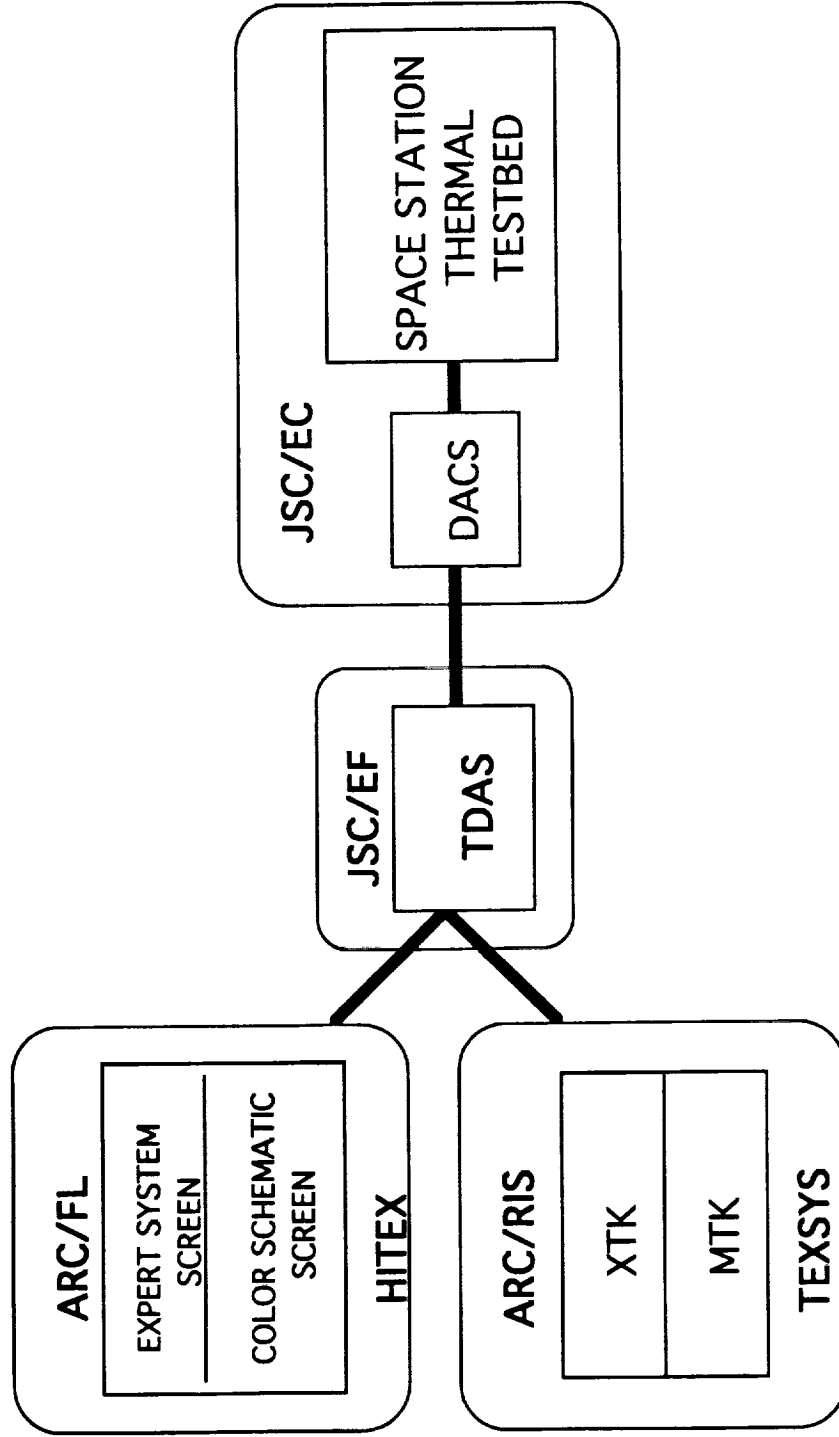


Figure 1. Thermal Expert System (TEXSYS) Architecture.

sensor values against the defined deadbands, significance limits, and alarm values, only significant sensor values are flagged to be sent to TEXSYS and HITEX. When no alarm values are violated, the significant data are forwarded after TDAS is polled; alarm violations are reported asynchronously to TEXSYS. TEXSYS can change the list of sensor readings examined and all sensor-associated limits.

4.3 Online model-based reasoning

The expert system was built using two software toolkits created by ARC. The Model ToolKit (MTK) was built to allow the rapid construction of qualitative models of physical systems.[3, 4] It features an object-oriented graphical interface to allow models to be built by selecting items from libraries and connecting them using a mouse. The Executive ToolKit (XTK) is a task language with constructs that allow symbolic processes to interact with low-level data acquisition and control processes.[5]

Rules for the propagation of sensor readings and data values, and the conversion of these to qualitative values, are included in the classes of component objects and are compiled by MTK into active values (daemons) before run time to enhance performance. In addition, a consistency-based diagnosis approach, using an assumption-based truth maintenance system (ATMS), is employed when inconsistent sensor readings are detected. Hypothetical worlds [globally-consistent belief sets] are generated corresponding to each candidate fault set. These fault candidates are obtained in a manner similar to that of de Kleer and Williams's General Diagnostic Engine (GDE) approach [6]. An assumption-based truth maintenance system (ATMS) [7] is used in TEXSYS to keep track of the chain of downstream facts which are justified by a given sensor reading. When a new reading arrives, the ATMS marks this previous chain as disbelieved, followed then by propagation and qualitative translations of the new reading in the model to generate a new chain of facts within the ATMS. TEXSYS marks the first time that consistency-based diagnosis and an assumption-based truth maintenance system have been used extensively in a realtime online controller application [4,8].

Rather than waiting for observations of future behavior to resolve ambiguous evidence, consideration of the thermal bus's past path in qualitative state space can be used to isolate faults. In MTK, this is implemented as a historian, which keeps a timestamped stack of the last five qualitative states for all parameters to which it was attached. Temporal reasoning on about ten percent of the model's parameters

provided sufficient information to distinguish all known fault modes with minimal additional overhead.

4.4 Procedural task execution

XTK includes a language for building tasks that are initiated by the expert system to carry out control and other actions on the system being monitored. Tasks are initiated in the expert system by establishing goals to be satisfied by the XTK tasks. Backward-chaining then causes the task or tasks needed to satisfy the goal to be started. The tasks that are written using XTK cannot be modified at run-time, but do have looping and branching conditionals and the ability to query the knowledge base, allowing the tasks to have a predefined range of responses to changing conditions.

5. Obstacles Overcome

5.1 Thermal bus hardware: target shifts, evolution

The development of TEXSYS was begun without the availability of most specific target system expertise. The three thermal bus testbeds at JSC evolved in parallel with TEXSYS software development. Because it was expected from the beginning that the thermal bus hardware design would vary during the course of software development, it was decided to adopt a device-centered approach to modeling in TEXSYS. For instance, the behavior of basic components such as filters and valves could be easily specified prior to knowledge of overall bus behavior. This device-centered approach was implemented easily as an object-oriented system, using a library of components to build schematic-like models. These models contained multiple instances of components, e.g., many individual solenoid valves. As the characteristics of two-phase thermal bus components became better known, the prototypical or parent-class definitions of given components were edited to reflect new knowledge, without explicitly altering the models -- a flexibility not found in unstructured AI approaches without inheritance, such as production systems.

In addition to parallel thermal hardware evolution, TEXSYS software development had to adapt to several changes in the identity of the thermal testbed targeted for delivery. Initial TEXSYS prototypes modelled portions of the then-planned Grumman thermal bus design. Subsequent changes in the targeted testbed were from a small-scale Grumman thermal brassboard to the Sundstrand thermal brassboard, and the

(similar) BATBS. This "moving target" problem itself demonstrated the value of a toolkit for rapid model editing -- the Model Toolkit, or MTK.

MTK's easy model modification capability allowed TEXSYS designers: (a) to reuse a high proportion of the knowledge base developed for the original target testbed in building later models of other testbed designs, and (b) during online testing with the BATBS, to modify the model to reflect a physically-removed valve -- in five minutes, compared with several days to modify and debug conventional procedural software (i.e., the DACS).

5.2 AI software performance

Initial TEXSYS prototypes used an ATMS together with interpreted forward-chaining, breadth-first KEE rules for propagation within the model as well as for matching faults. The first tests of TEXSYS with the Sundstrand thermal brassboard model in July 1988 consumed roughly three hours per update cycle -- orders of magnitude slower than required -- given just four new sensor readings per cycle.

This led to the design of a rule compiler (written by John Nienart) in which all rules were transformed into small compiled Lisp functions attached to locations in the model. Using this compilation approach, the comparable update cycle time for TEXSYS was reduced to about ten seconds -- thereby achieving real-time performance levels for the thermal bus domain. Without this performance improvement, no realtime control would have been possible for TEXSYS.

Even with the rule compiler in use, voluminous data updates associated with BATBS startup tended to slow TEXSYS to about 30-45 seconds/cycle. Furthermore, certain control actions during startup required faster-than-usual TEXSYS performance. In this case, performance requirements were met by widening the TDAS update deadbands for all non-startup-critical sensors to large values, effectively filtering out updates from these non-critical sensors during startup. Certain time-critical valve sequencing functions during startup were implemented as separate, subsidiary closed-loop controllers (written in the XTK language).

5.3 Hypothetical reasoning slowness

During TEXSYS development tests at ARC with the Sundstrand thermal brassboard, it was noticed that occasionally some faults induced symptoms which were not significantly different than those induced by other known faults. One initial approach

discussed to resolving this fault mode ambiguity was to carry forward multiple candidate sets of faults as separate candidate worlds, and to then wait for future snapshots of bus behavior to hopefully confirm one world as reality. However, it was found that model update times rose linearly with the number of existing worlds. Given that TEXSYS's normal cycle time was about twenty seconds with only a single baseline world, and given an imposed cycle-time ceiling of one minute, the competing-hypotheses approach to ambiguous faults was not feasible without replacing the worlds and truth-maintenance systems with a more efficient non-commercial implementation -- at a late stage of TEXSYS development. Therefore, ARC researchers created a hybrid rule- and model-based approach.

It was necessary in this hybrid approach to reduce the reliance on consistency-based diagnosis for trapping all faults, except for bad sensors and previously-unknown or unforeseen faults. The KEE ATMS was then typically used only as a justification-based TMS except for these sensor conflict and unexpected faults. In retrospect, it is not likely that a solely model-based approach could have replaced all rule-based reasoning in this domain, even with much faster computers, given the existence of highly nonlinear, heuristically-modelled components in the BATBS model.

6. Project Course

The expert system and human interface software were developed as prototypes of increasing capability and complexity over a period of 18 months. Given a dearth of detailed thermal bus knowledge, software development was focussed during this time on implementing basic reasoning and modelling techniques in the MTK and XTK toolkits. Each successive prototype of the expert system and human interface was refined based on comments from human factors scientists at ARC and the thermal bus experts and users at JSC. The first several prototypes demonstrated were standalone systems and were not attached to any hardware. These prototypes were used to validate the basic thermal knowledge obtained from the experts, to educate the users as to the capabilities of expert systems and to explore some human interface design concepts. Later prototypes were tested with LDAS and the Sundstrand thermal brassboard at ARC.

These ARC brassboard tests were used to validate the basic TEXSYS design, discover any gross gaps in thermal bus knowledge, resolve timing problems, and verify proper control of the thermal bus. Demonstrations of prototype versions of

TEXSYS with the Sundstrand brassboard were given to NASA Administrator James Fletcher (September 1988) and to Associate Administrator of the Office of Space Station (OSS) Jim Odum (November 1988).

After delivery to JSC of the BATBS hardware, a set of tests was run by the domain experts to examine the operation of the bus and evaluate it for use on the space station. Fabrication delays in the delivery of the Grumman brassboard hardware forced a switch to the BATBS design in the spring of 1988. The operational experience gained by the experts from the BATBS tests was then used to generate three documents for use in creating the operational TEXSYS: a physical description of the bus and its general behavior; a nominal operations document that explained all procedures for operations such as startup, shutdown and setpoint change; and a fault diagnosis and recovery procedures document that characterized known BATBS faults. Together with hands-on tests with the Sundstrand brassboard, these three documents formed the basis for the ARC-developed knowledge base. The ARC staff then spent six months developing and testing the TEXSYS knowledge base, which was delivered to JSC in February, 1989. ARC technical staff were then posted to JSC on a continuous, rotating basis until the final JSC demonstration in August, 1989.

A group of JSC staff meanwhile drafted a plan for the integration and testing of the TEXSYS/HITEX/TDAS system after delivery from ARC. Following the outline in this test plan, several weeks of testing was performed to check connectivity between the various subsystems. The next set of tests was performed at JSC by engineers from both NASA centers, using recorded data from the earlier BATBS fault injection tests. These tests used the playback of data for a particular nominal operation or fault to validate the TEXSYS model and its diagnostics for that operation or fault. This was the first comprehensive testing of the knowledge bases with real data from the BATBS, and it required six weeks, through mid-July, 1989.

Finally, another six weeks of testing was performed, with the entire TEXSYS system online with the live BATBS at JSC. This testing involved two shifts of operations and methodically worked through the nominal operations and faults covered by the expert system. Many revisions to the knowledge base and operations tasks were made as more experience with the bus was gained. For example, it was found that for the BPRV failure fault, the time lag between fault injection, appearance of initial symptoms and appearance of symptoms that allow the differentiation and isolation of the fault was much shorter than initially anticipated, as the bus was more stable than had been

predicted by earlier tests. The software systems were frozen at the end of this testing period. The final TEXSYS system in September, 1989, contained 340 rules and over 3400 frames in the model, and 146 tasks for recovery and nominal control.

After the online testing was completed, a two week formal test and demonstration was conducted in late August, 1989. All of the nominal operations and fault procedures were successfully performed. These were extensively documented with screen hardcopies and printouts of justifications of fault diagnoses (see Appendix A). In addition, formal briefings and demonstrations were given for senior NASA management of ARC and JSC, and for key Space Station Freedom managers (Level I and II) and Work Package 2 contractors in the thermal and automation groups.

7. Final Demonstration Results at JSC

In tests run with the BATBS at the NASA Johnson Space Center in August, 1989, TEXSYS successfully performed real-time monitoring and control (such as valve actuation) during all nominal modes of operation such as startup and setpoint changes. TEXSYS successfully noticed and reacted to all of the required seventeen BATBS faults shown in Figure 2. Multiple faults were often encountered -- the TEXSYS architecture proved to be capable of recognizing multiple independent faults, both in parallel and serially. Unplanned faults were also demonstrated, such as a shorting solenoid valve which was noticed due to a conflict in local temperatures caused by its radiated excess heat. Since any given system-level fault can be induced by any of several component faults, and only about a third of these known component faults were included in the formal demonstration, unplanned component faults were fairly common. In these cases, TEXSYS identified the system-level fault even when it didn't recognize the component fault causing the problem. During these tests, TEXSYS update cycle times were about 10-30 seconds, but varied between five seconds to about a minute, depending on the quantity of data updated in a given cycle. When sensor conflicts caused hypothetical worlds to be created, the latter duration could stretch to several minutes, thereby violating user requirements.

An example of a system and component-level fault is given in Figure 3, in which a stuck-closed valve (component fault mode) causes the total flow through the evaporators (BFM701) to drop abnormally (system fault mode) and the downstream heat exchanger temperature (BTC005) to rise due to lack of fluid. TEXSYS noted the drop in flow immediately and advised the operator. After BTC005 rose beyond the

SPECIFIC FUNCTIONALITY DEMONSTRATED

NOMINAL OPERATIONS

- **START UP**
- **SET POINT CHANGES**
- **SHUT DOWN**

Auto/Man Realtime Controls in
Startup, Setpoint Chg., Shutdown,
and FDIR elements 2, 3, 5.

Realtime Diagnosis and
Advice in FDIR elements 1,4,6,7.

FAULT DETECTION, ISOLATION, AND RECOVERY

- **7 SYSTEM LEVEL FAULTS**
 - 1. FLUID INVENTORY OUT OF TOLERANCE
 - 2. RFMD POWER DRAW OUT OF TOLERANCE
 - 3. EVAPORATOR LOOP FLOW OUT OF TOLERANCE
 - 4. INADEQUATE SUBCOOLING
 - 5. SETPOINT NOT STABLE/TRACKING
 - 6. EVAPORATOR(S) TEMPERATURE NOT STABLE
 - 7. ERRONEOUS INSTRUMENTATION
- **10 COMPONENT LEVEL FAULTS**
 - 1a. SLOW LEAK
 - 2a. RFMD MOTOR FAILED
 - 3a. SINGLE EVAPORATOR BLOCKAGE
 - 4a. HIGH COOLANT SINK TEMPERATURE
 - 5a. BPRV FAILURE
 - 5b. BUILDUP OF NON-CONDENSIBLE GASES
 - 6a. BPRV ACTUATOR FAILURE
 - 6b. EXCESSIVE HEATLOAD ON SINGLE EVAPORATOR
 - 7a. ACCUMULATOR POSITION SENSOR FAILURE
 - 7b. PRESSURE SENSOR FAILURE

Figure 2. Major and component faults required for the demonstration. (Other faults were also tested.)

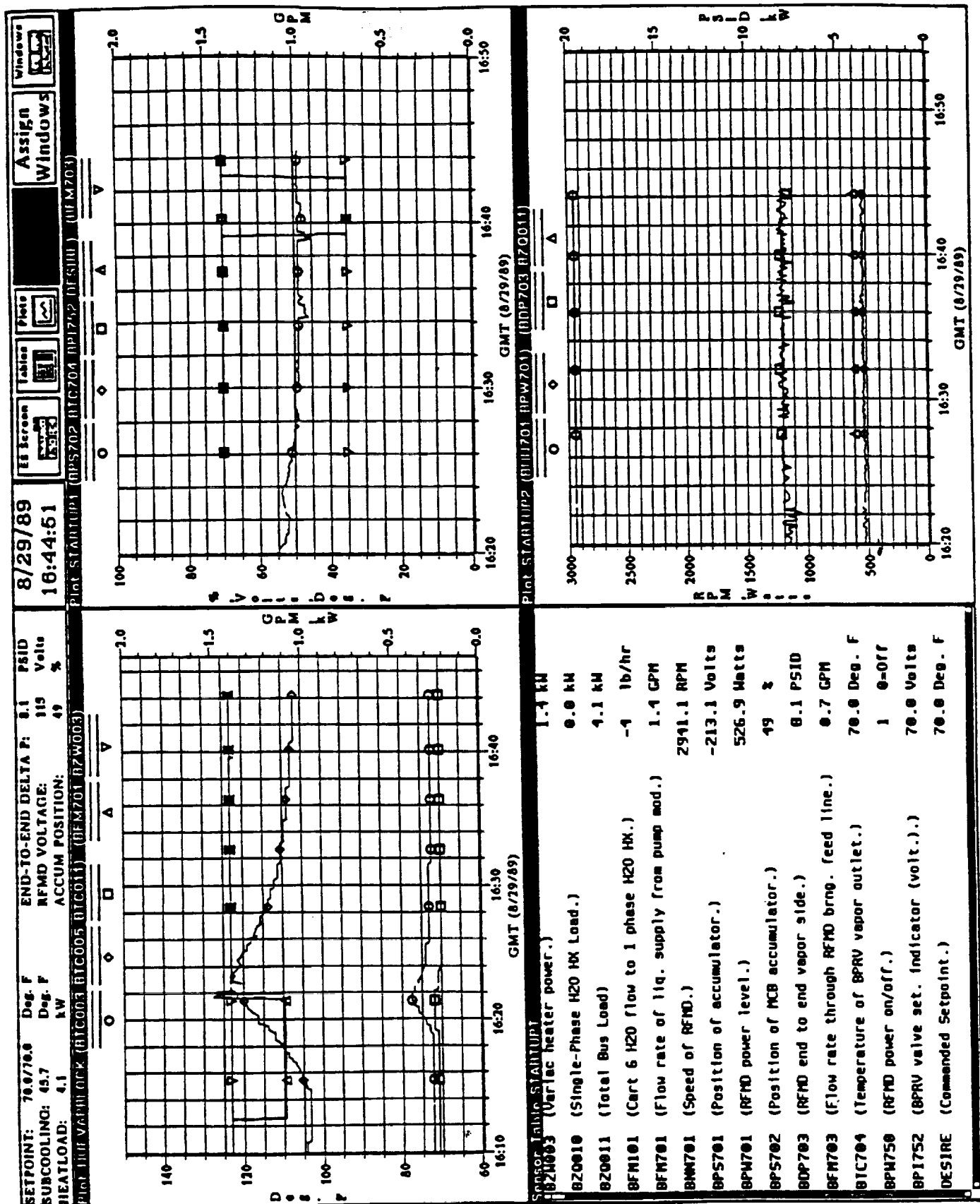


Figure 3. Single evaporator blockage fault, affecting the two-phase-water heat exchanger. This fault and similar faults may be found in Appendix A.

expected range for the current heat load, TEXSYS notified the operator of a possible blockage fault, and toggled the isolation valve to confirm the fault. Toggling the valve restored normal flow, indicating a previously-stuck valve.

7.1 Gradual Acceptance by Users

Given significant mistrust of AI techniques by the thermal engineers, initial TEXSYS online tests were conducted with all control actions subject to operator approval. As user confidence in the software increased, they gradually allowed TEXSYS direct control of the BATBS. After a month of online testing with the BATBS, it was noticed that the thermal engineers were comfortable with taking their attention away from their telemetry displays when they knew that TEXSYS was on line (e.g., informal discussions, taking bathroom breaks, etc.), leaving only an operator at the human interface console and a technician by the BATBS kill switch. The thermal engineers consider TEXSYS to be a significant improvement over their previous fault detection and data display capability, but criticize its occasional slowdowns (usually due to worlds processing). Faster computers and further code rewrites would have helped these slowdowns.

7.2 Model-Based Benefits Shown

In addition to simplifying and reducing the number of rules needed for fault recognition (only 340 rules in 190,000 total lines of code), the use of a device-oriented model-based approach in TEXSYS allowed prototyping to begin over a year before a target thermal bus design was selected. Conversion from the (original) Grumman thermal bus design to the thermal brassboard and the BATBS simply required the addition of some classes of specialized hardware to the component library, e.g., pitot pumps in addition to ordinary vane pumps. Rules referring only to components and fault modes common to all thermal busses were reused, reducing development effort.

Another benefit of the device-oriented modelling approach was the ability to edit the arrangement of components in the model, to follow repairs or damage, without changing the fault recognition rules or altering the conflict resolution system software. When a broken valve was replaced with a length of pipe during testing, this capability allowed TEXSYS to be brought offline, the corresponding model component removed, the ATMS reinitialized, and TEXSYS brought back online in about twenty minutes. In comparison, according to the thermal engineers, the same change made to the Fortran-based DACS would have taken at least four days. Finally, a model-based

approach was found to ease knowledge acquisition, as non-Lisp-versant thermal engineers could reason in terms of device interactions in a schematic representation more easily than they could debug complex rules.

7.3 Benefits of Hands-on Brassboard Testing

Early hands-on experience with thermal bus hardware in a research environment (the Sundstrand brassboard) at ARC was also beneficial. Total running time of the brassboard at ARC actually exceeded that of the BATBS during later testing at JSC. Early problems with online diagnosis of brassboard failures pushed MTK improvements and knowledge base refinements, and most timing issues during thermal bus startup and shutdown were resolved in brassboard tests. Unexpected failures, lack of consistent performance, and unmodeled nonlinearities were all features of the brassboard. If instead a simulation had been employed at ARC during software development, it is unlikely that these problems would have been discovered or addressed until software field deployment at JSC.

7.4 Organizational impact and follow-on activities

The TEXSYS program was a proof-of-concept with respect to the use of model-based symbolic control in a real-time environment. While it was a successful demonstration, its software and hardware were predominantly Lisp-based and hence are presently unsuitable for SSF onboard use. The model-based control approach (of which TEXSYS is an example) is now being used by the SSF Work Package 2 prime contractor to create a thermal bus control successor to TEXSYS, which will function in the SSF onboard computing environment (Ada software in a Unix-based environment, running on parallel Intel 80386-based computers) [9]. By demonstrating that AI techniques can be reliably used to monitor and control complex space subsystems such as the BATBS, the TEXSYS project has made NASA management and thermal engineers more willing to consider the future use of AI techniques in Space Station Freedom and Lunar/Mars mission thermal control software.

Development of a similar knowledge-based system is now underway for Space Station Freedom power distribution and is being considered for planned closed-loop life support systems. The model-based approach developed for TEXSYS and the XTK toolkit are being used for development of a life support design workstation [10].

8. Summary

The success of the hierarchical symbolic model-based control approach taken in TEXSYS demonstrates that a layered symbolic controller can be used to successfully control complex hardware in real time. The use of qualitative model-based and temporal reasoning in TEXSYS is one of the first applications of these techniques to online, real-time process control. TEXSYS successfully makes use of an incomplete causal model and identifies multiple independent faults with it.

It is too soon to say if the TEXSYS demonstrations will ultimately lead to a spaceborne diagnostic system, but they show that AI techniques can be effectively applied to real-time control of large electromechanical systems, such as those planned as part of Space Station Freedom and future lunar and Mars bases. A generic, component-oriented modelling approach is recommended in order to follow dynamic hardware configurations. A component-oriented rather than a system-oriented approach can avoid much rewriting of rules when components are rearranged in a device, as often happens during repairs, upgrades, and design changes of complex mechanisms. The operational success of TEXSYS demonstrates that a range of techniques (model-based and qualitative reasoning, classification systems, frame-based representations, temporal reasoning, and procedural reasoning) can be used together to control and diagnose faults in certain relevant electromechanical systems in real time. Given their success in the TEXSYS demonstration, the model-based symbolic control methods used are a promising general approach to the automation of the monitoring and control of manned spacecraft subsystems.

The payoff of this automation is threefold: increased likelihood of mission success, or improved robustness; reduced operations costs; and, increased crew scientific productivity. Given automated monitoring and control as shown in the TEXSYS demonstrations, incipient and time-dependent faults can be automatically detected and warnings issued to crew or corrective action taken prior to catastrophic failures. This automated monitoring capability should also reduce the burden on human subsystem monitoring and thence reduce recurring mission operations costs. Finally, the automation of routine subsystem housekeeping functions will reduce their share of crew work schedules, thus freeing crew members for more intrinsically useful activities.

9. Notes on Volume Two and Appendices

In contrast with the overview given in this volume, the testing of TEXSYS with the BATBS hardware and the design and use of SADP software are discussed in detail in Volume Two and Appendices A and B, respectively. Volume Two and Appendix A were written by the Crew and Thermal Systems Division at JSC as their final TEXSYS test report. Appendix B is a collection of TEXSYS software design documents and toolkit user guides, written by the software developers at ARC and JSC over the past eighteen months. Given the disparate sources, the format and style varies between documents.

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